

Constraints on Unparticles from Low Energy Neutrino-Electron Scattering

A. B. Balantekin*

Department of Physics, University of Wisconsin, Madison, WI 53706, USA

K. O. Ozansoy†

Department of Physics, University of Wisconsin, Madison, WI 53706, USA and

Department of Physics, Ankara University, 06100 Tandogan, Ankara, Turkey

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We place limits on scalar and vector unparticle couplings to electrons and neutrinos using data from reactor neutrino experiments originally designed to search for neutrino magnetic moment. Upper bounds on Standard Model lepton-scalar unparticle and lepton -vector unparticle couplings λ_0 , and λ_1 are given for various values of the unparticle mass dimension d , and the unparticle energy scale Λ_U . Especially for smaller values of the mass dimension d ($1 < d < 1.3$) these bounds are very significant and comparable to those obtained from production rates at high energy colliders. These bounds are also similar to those obtained by the analysis of the absence of the decay of the low-energy solar and reactor neutrinos.

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I. INTRODUCTION

Georgi suggested that a scale invariant sector which decouples at a sufficiently large energy scale may exist [1]. Presence of this sector could yield very interesting physics beyond the Standard Model and should be accessible at colliders. If such a scale invariance occurs in nature, it cannot be described in terms of particles. In this scheme the hidden sector with a non-trivial infrared fixed point, described by the Banks-Zaks (BZ) [2] operators \mathcal{O}_{BZ} and the Standard Model sector, described by the operators \mathcal{O}_{SM} interact through the exchange of particles with a mass scale of \mathcal{M}_U^k :

$$\frac{1}{\mathcal{M}_U^k} \mathcal{O}_{BZ} \mathcal{O}_{SM}, \quad (1)$$

where BZ and Standard Model operators have the mass dimension d_{BZ} and d_{SM} , respectively. Below the infrared fixed point Λ_U , the BZ operators \mathcal{O}_{BZ} mutate into unparticle operators and Eq. (1) reduces to

$$\frac{C_U \Lambda_U^{d_{BZ}-d}}{\mathcal{M}_U^k} \mathcal{O}_{BZ} \mathcal{O}_{SM}, \quad (2)$$

where d is the non-integral scaling mass dimension of the unparticle operator \mathcal{O}_U , and the constant C_U is the coefficient of the relevant operators. (Note that in Ref. [1] the scale dimension is defined by d_U).

Following Georgi's original paper there has been significant activity investigating phenomenological consequences of the unparticle sector. Implications of the interference of the Standard Model amplitudes and amplitudes with virtual unparticles were considered in [3]. Collider phenomenology of unparticle physics has been explored in a great detail, and Feynman rules for spin 0, spin 1, or spin 2 unparticles coupled to a variety of Standard Model gauge invariant operators have been explicitly given in Ref. [4]. Subsequently many authors studied possible signatures of unparticle sector in collider experiments [5, 6, 7, 8, 9, 10]. Although the small magnitude of the coupling between unparticles and Standard Model could conceal the unparticle phenomena at low energies, unparticle physics can nevertheless be constrained using data from non-accelerator physics. Limits have indeed been placed on unparticle - Standard Model particle couplings from cosmology, especially big-bang nucleosynthesis [11], from avoidance of supernova overcooling by unparticle emission [11, 12, 13], and from the limits on the decay of solar and reactor neutrinos in oscillation experiments [14].

*Electronic address: baha@physics.wisc.edu

†Electronic address: oozansoy@physics.wisc.edu

In this paper, we consider a complementary non-accelerator limit on unparticle-Standard Model couplings, namely very low-energy elastic neutrino-electron scattering experiments. Typically such experiments are performed at sources that emit a large number of neutrinos such as reactors and their search for physics beyond Standard Model is characterized by the neutrino magnetic moment. (For a recent review see e.g. Ref [15]). Nevertheless, the data from such experiments can also be used to search for other physics beyond the Standard Model. In the next section we place limits on scalar and vector unparticle couplings to electrons and neutrinos using data from reactor neutrino experiments originally designed to search for neutrino magnetic moment. We find that our limits are comparable to those obtained from the decay bounds of solar and reactor neutrinos.

II. ANTINEUTRINO-ELECTRON SCATTERING AT REACTORS

The differential Standard Model cross section for electron antineutrinos on electrons is given by [16]

$$\frac{d\sigma}{dT} = \frac{G_F^2 m_e}{2\pi} \left[(g_V + g_A)^2 + (g_V - g_A)^2 \left(1 - \frac{T}{E_\nu}\right)^2 + [g_A^2 - g_V^2] \frac{m_e T}{E_\nu} \right], \quad (3)$$

where T is the electron recoil kinetic energy, $g_V = 2\sin^2\theta_W + \frac{1}{2}$, $g_A = \frac{1}{2}$ for ν_e , $g_A = -\frac{1}{2}$ for $\bar{\nu}_e$. Low-energy antineutrino-electron elastic scattering experiments typically search for excess counts beyond the Standard Model contribution given in Eq. (3).

Interactions between Standard Model leptons and the scalar unparticles are given by [3, 4, 8]

$$\lambda_{0e} \frac{1}{\Lambda^{d-1}} \bar{e} e O_U + \lambda_{0\nu}^{\alpha\beta} \frac{1}{\Lambda^{d-1}} \bar{\nu}^\alpha \nu^\beta O_U + \text{h.c.} \quad (4)$$

Therefore, the contribution to the scattering amplitude for elastic $\bar{\nu}_e$ - e scattering from the exchange of the scalar unparticle takes the form

$$\mathcal{M}_{\mathcal{U}_S} = \frac{f(d)}{\Lambda_{\mathcal{U}}^{2d-2}} [\bar{\nu}_\beta(k') \nu_\alpha(k)] [\bar{e}(p') e(p)] [-q^2 - i\epsilon]^{d-2}, \quad (5)$$

where

$$f(d) = \frac{\lambda_{0\nu}^{\alpha\beta} \lambda_{0e} A_d}{2 \sin(d\pi)}, \quad (6)$$

and

$$A_d = \frac{16\pi^{5/2}}{(2\pi)^{2d}} \frac{\Gamma(d+1/2)}{\Gamma(d-1)\Gamma(2d)}. \quad (7)$$

In writing Eqs. (5) and (6) we included the possibility that scalar unparticle exchange may change the neutrino flavor. In our analysis for scalar unparticles, we use the short-hand notation $\lambda_0 \equiv (\lambda_{0\nu} \lambda_{0e})^{1/2}$. The interference term between the scalar unparticle amplitude and the Standard Model amplitude is proportional to the neutrino mass (or more precisely to m_ν/Λ) and we neglect its contribution to the cross section. The contribution to the differential scattering cross section from the exchange of the scalar unparticle then takes the form

$$\frac{d\sigma}{dT} = \frac{f(d)^2 2^{(2d-7)}}{\pi E_\nu^2 \Lambda_{\mathcal{U}}^{4d-4}} (m_e T)^{(2d-3)} (T + 2m_e). \quad (8)$$

For small electron recoil energies ($T < 2m_e$), this cross-section depends on T as $1/T^{(3-2d)}$. Hence as T gets smaller the differential cross section gets larger for $d < 3/2$. This behavior is reminiscent of the T -dependence of the neutrino magnetic moment contribution, which goes like $\sigma \sim \mu^2/T$. If d were allowed to take the value $d = 1$, the cross section in Eq. (8) would behave just like the magnetic moment cross section. For this reason experiments designed to search for neutrino magnetic moment are particularly appropriate to place limits on unparticle couplings, especially for values of d close to 1.

Interactions between Standard Model leptons and the vector unparticles are given by [3, 4, 8]

$$\lambda_{1e} \frac{1}{\Lambda^{d-1}} \bar{e} \gamma_\mu e O_U^\mu + \lambda_{1\nu}^{\alpha\beta} \frac{1}{\Lambda^{d-1}} \bar{\nu}^\alpha \gamma_\mu \nu^\beta O_U^\mu + \text{h.c.} \quad (9)$$

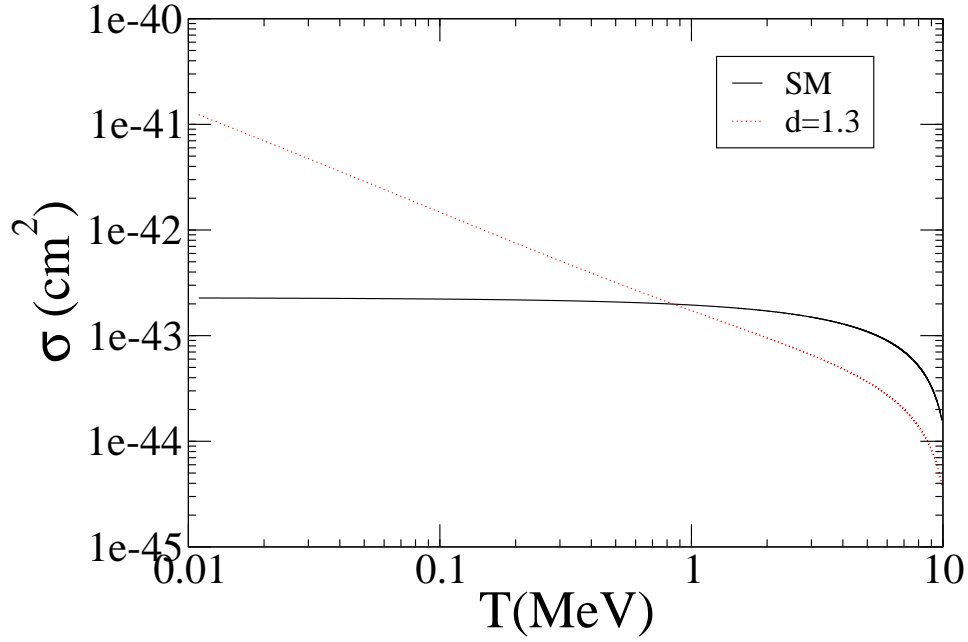


FIG. 1: Folded differential cross sections from the Standard Model and scalar unparticles. Solid curve is for the Standard Model and the dashed one for the scalar unparticle. We assumed $d = 1.3$, $\Lambda_{\mathcal{U}} = 1$ TeV, and $\lambda_{0\text{max}} = 0.001$.

Hence the contribution to the scattering amplitude for elastic $\bar{\nu}_e$ - e scattering from the exchange of the vector unparticle takes the form

$$\mathcal{M}_{\mathcal{U}_V} = \frac{f(d)}{\Lambda_{\mathcal{U}}^{2d-2}} [\bar{\nu}_\beta(k') \gamma_\mu \nu_\alpha(k)] [\bar{e}(p') \gamma_\nu e(p)] [-P^2 - i\epsilon]^{d-2} \pi^{\mu\nu}(P), \quad (10)$$

where

$$\pi_{\mu\nu}(P) = -g^{\mu\nu} + \frac{P^\mu P^\nu}{P^2}. \quad (11)$$

Similar to the scalar unparticle case we use the short-hand notation $\lambda_1 \equiv (\lambda_{1\nu} \lambda_{1e})^{1/2}$. The contribution to the differential scattering cross section from the exchange of the vector unparticle then takes the form

$$\frac{d\sigma}{dT} = \frac{(f(d))^2 (2)^{(2d-8)}}{\pi \Lambda_{\mathcal{U}}^{4d-4}} (m_e)^{2d-3} (T)^{(2d-4)} \left[1 + \left(1 - \frac{T}{E_\nu}\right)^2 - \frac{m_e T}{E_\nu^2} \right] \quad (12)$$

Nuclear reactors emit copious ($\sim 10^{20}$ per second) electron antineutrinos with energies up to about 10 MeV. The exact energy spectrum depends on the specific fuel composition of the reactor. As an example, reactor neutrino spectrum coming from the fissioning of ^{235}U is approximately given by [16]

$$\frac{dN_\nu}{dE_\nu} \sim \exp(0.870 - 0.160E_\nu - 0.0910E_\nu^2), \quad (13)$$

where the antineutrino energy, E_ν , is given in MeV. The pertinent quantity for these elastic scattering experiments is the folded cross-section:

$$\left\langle \frac{d\sigma}{dT} \right\rangle = \int_{E_\nu^{\min}(T)}^{\infty} \frac{dN_\nu}{dE_\nu} \frac{d\sigma(E_\nu)}{dT} dE_\nu, \quad (14)$$

where $E_\nu^{\min}(T) = 0.5(T + \sqrt{T^2 + 2Tm_e})$. In Figure 1 we contrast schematic behaviors of the Standard Model cross section and the cross section from the scalar unparticle exchange folded with the reactor spectrum. In the calculations leading to this figure we assumed that $d = 1.3$, $\Lambda_{\mathcal{U}} = 1$ TeV, and $\lambda_{0\text{max}} = 10^{-3}$. The figure indicates that at low electron recoil energies the unparticle contribution could measurably change the total count rate. As in the neutrino

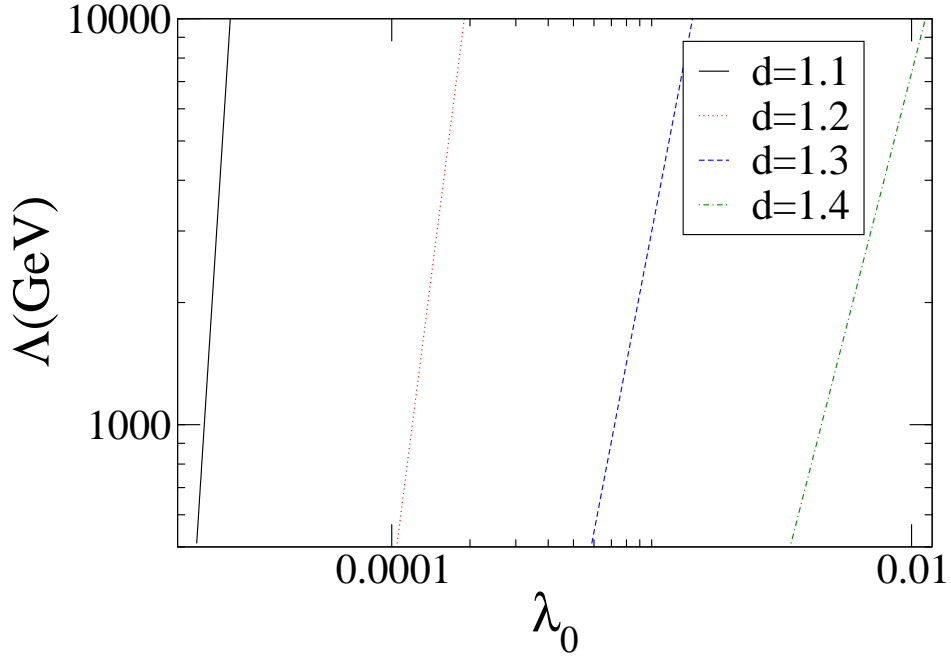


FIG. 2: Upper limits on the maximum value of the scalar unparticle coupling parameter λ_0 for different energy scales $\Lambda_{\mathcal{U}}$ obtained using the TEXONO data.

magnetic moment searches, the crucial quantity is the minimum electron recoil energy accessible to the experiment. Current experimental status of neutrino magnetic moment searches is summarized by the Particle Data Group [17]. Two recent experiments are the MUNU experiment with an energy threshold of 700 KeV [18] and the TEXONO experiment with a threshold of 5 KeV [19].

In our calculations, we fix the unparticle mass dimension d to specific values. Upper limits on the coupling constants λ_0 , and λ_1 with $\Lambda_{\mathcal{U}} = 1$ TeV for various values of the mass dimension d , obtained from the analysis of the TEXONO data are shown in Table I, and Table II. Future experiments are expected to try lowering the energy threshold. Figure 1 clearly indicates that, if lower energy thresholds can be achieved, limits on the coupling constants can be significantly tightened. Since the cross section is proportional to the combination $\lambda^4/\Lambda_{\mathcal{U}}^{4d-4}$, in principle it is this quantity that can be extracted from the low-energy elastic electron-antineutrino scattering data. The resulting scaling behavior for the scalar and vector unparticle couplings are illustrated in Figures 2 and 3, respectively. In these figures, the parameter space to the right of a particular line is ruled out by the TEXONO data for the indicated value of d .

TABLE I: For $\Lambda_{\mathcal{U}} = 1$ TeV, upper limits of coupling constant λ_0 for various values of mass dimension d .

d	λ_{0max}
1.01	3.5×10^{-6}
1.05	7.3×10^{-6}
1.1	1.9×10^{-5}
1.2	1.2×10^{-4}
1.3	7.2×10^{-4}
1.4	4.5×10^{-3}
1.5	2.7×10^{-2}
1.7	9.5×10^{-1}
1.9	24.5

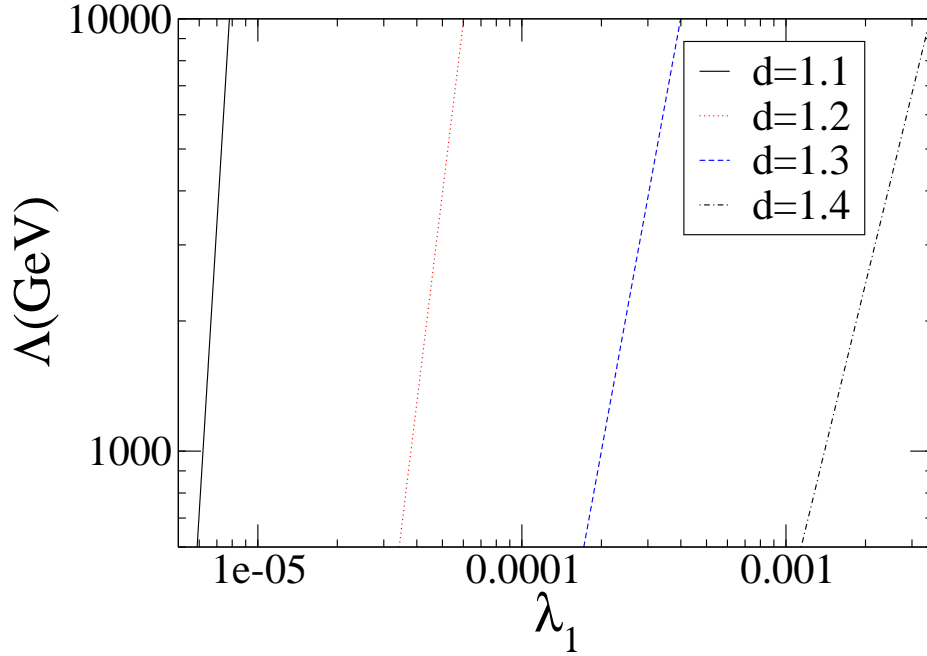


FIG. 3: Upper limits on the maximum value of the vector unparticle coupling parameter λ_1 for different energy scales Λ_U obtained using the TEXONO data.

III. CONCLUSIONS

We obtained bounds on the coupling of the unparticle sector to electron and electron neutrinos using elastic scattering data from reactors. Especially for smaller values of the mass dimension d , ($1 < d < 1.3$) these bounds are very significant and comparable to those obtained from production rates at high energy colliders. These bounds are also similar to those obtained by the analysis of the absence of the decay of the low-energy solar and reactor neutrinos [14]. Both our bounds and those obtained in Ref. [14] imply that there still is a considerable window of the parameter space for possible discovery of the unparticle sector at LHC. Note that even though the astrophysical constraints are more restrictive in some cases than our limits, it is worth pointing out that ours are *direct* experimental limits and as such they are subject to fewer uncertainties than the astrophysical limits.

One should finally remark that unparticle couplings could change neutrino flavor, and may also convert active neutrino flavors into sterile ones. Even though such processes may have interesting astrophysical implications [20], they are unlikely to provide better bounds on unparticle couplings.

TABLE II: For $\Lambda_U = 1$ TeV, upper limits of coupling constant λ_1 for various values of mass dimension d .

d	λ_{1max}
1.01	1.1×10^{-6}
1.05	2.4×10^{-6}
1.1	6.2×10^{-6}
1.2	3.8×10^{-5}
1.3	2.0×10^{-4}
1.4	1.4×10^{-3}
1.5	9.1×10^{-3}
1.7	3.1×10^{-1}
1.9	8.1

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